

MAGNETOSPHERIC MULTISCALE MISSION NAVIGATION PERFORMANCE DURING APOGEE-RAISING AND BEYOND

Mitra Farahmand,^{*} Anne Long,[†] Jacob Hollister,[‡] Julie Rose,[‡] Dominic Godine[‡]

The primary objective of the Magnetospheric Multiscale (MMS) Mission is to study the magnetic reconnection phenomena in the Earth's magnetosphere. The MMS mission consists of four identical spinning spacecraft with the science objectives requiring a tetrahedral formation in highly elliptical orbits. The MMS spacecraft are equipped with onboard orbit and time determination software, provided by a weak-signal Global Positioning System (GPS) Navigator receiver hosting the Goddard Enhanced Onboard Navigation System (GEONS). This paper presents the results of MMS navigation performance analysis during the Phase 2a apogee-raising campaign and Phase 2b science segment of the mission.

INTRODUCTION

On March 12, 2015, NASA Goddard Space Flight Center (GSFC) launched the Magnetospheric Multiscale (MMS) spacecraft. The MMS mission consists of four identical spinning spacecraft with one of the most complex flight dynamics concepts to date. The MMS science objectives require tetrahedral formations of varying dimensions flying in highly elliptical orbits. There are two science phases in which the science region of interest (RoI) is centered at the apogee of the orbits. In Phase 1, the day-side magnetopause and, in Phase 2, the night-side neutral sheet in the magnetotail are studied. During Phase 1, a series of maneuvers was executed to decrease the spacecraft formation scale-size from a 160 km to a 7 km separation in the RoI while flying on a $1.2 \text{ Earth Radii (Re)} \times 12 \text{ Re}$ orbit. The transition from Phase 1 to Phase 2 was made during the apogee-raising campaign (aka Phase 2a), where eight maneuvers per spacecraft were completed to raise the apogee radius from 12 Re to 25 Re. In the science segment of Phase 2 (aka Phase 2b), a series of maneuvers was executed to reduce the formation scale-size from a 160 km to a 20 km separation in the RoI while on a $1.2 \text{ Re} \times 25 \text{ Re}$ orbit.

The MMS spacecraft hosts an onboard orbit and time determination capability provided by the weak-signal Global Positioning System (GPS) Navigator receiver with embedded Goddard Enhanced Onboard Navigation System (GEONS) flight software. Phase 1 and Phase 2a (the apogee-raising campaign) of MMS mission were completed successfully, and currently Phase 2b is nearing completion. Farahmand et al. discusses the remarkable performance of the MMS navigation system during the first 6 months of the mission¹. For the remainder of Phase 1, which lasted until February

^{*} Senior System Engineer, a.i. solutions, 4500 Forbes Blvd, Lanham, MD 20706.

[†] Consulting System Engineer, a.i. solutions, 4500 Forbes Blvd, Lanham, MD 2070.

[‡] Junior System Engineer, a.i. solutions, 4500 Forbes Blvd, Lanham, MD 2070.

of 2017, the MMS navigation system remained consistently reliable and the navigation requirements were met with significant margins.

This paper presents the results of MMS navigation performance analysis during the Phase 2a apogee-raising campaign and Phase 2b science segment of the mission. The main objective is to demonstrate that the onboard orbit solutions meet the definitive, predictive, and maneuver planning requirements defined by the MMS mission. The following sections provide an overview of the MMS onboard navigation system, a discussion of the GEONS performance assessment process, and GEONS navigation analysis results for both Phase 2a and 2b. The conclusion summarizes the results and discusses expectations for the navigation performance during the extended mission.

MMS ONBOARD NAVIGATION SYSTEM

The MMS onboard navigation system meets the MMS high accuracy orbit and time determination requirements by 1) acquiring and tracking GPS L1 signals using the GSFC-developed Navigator receiver and 2) processing GPS Pseudorange (PR) measurements referenced to an Ultra Stable Oscillator (USO) in the GEONS flight software. The Navigator receiver's weak-signal acquisition capability enables the MMS spacecraft to track GPS signals well above the GPS constellation². The GEONS flight software uses an Extended Kalman Filter (EKF) with a high-fidelity dynamics model to estimate the spacecraft's position, velocity, clock bias, clock bias rate, and clock bias acceleration. The GEONS EKF ingests high-resolution thrust acceleration measurements from the onboard accelerometer within the Attitude Control System (ACS) to model the frequent formation resize and formation maintenance maneuvers performed during the science segments of the mission and apogee-raising (AR) maneuvers executed during Phase 2a.

GEONS PERFORMANCE ASSESSMENT PROCESS

During the first two months of the commissioning period, the GSFC Flight Dynamics Facility (FDF) was nominally the primary provider of MMS navigation solutions. Early in the mission, the MMS flight dynamics team at Flight Dynamics Operations Area (FDOA) compared GEONS solutions against FDF solutions; these comparisons demonstrated that the GEONS solutions were accurate and reliable¹. Therefore, the MMS flight dynamics team started using GEONS navigation solutions for maneuver planning soon after launch and continued using these solutions throughout Phase 1, which continued for almost two years. Before the apogee-raising campaign, FDOA requested that FDF perform mission proficiency tests in preparation for the delivery of navigation solutions if a GEONS failure occurred onboard an MMS spacecraft during the large AR maneuvers. The apogee-raising maneuvers were particularly critical to the success of the remainder of MMS mission since missing a single maneuver could significantly impact the start and length of Phase 2b. Because the apogee-raising maneuvers were executed as planned, the MMS flight dynamics team continued using the GEONS solutions throughout Phase 2, and the FDF provided navigation solutions for evaluation of the accuracy of the onboard solutions a few times during the apogee-raising and science phases.

MMS definitive navigation performance is evaluated by comparing the FDF definitive solutions with the GEONS filtered solutions. The FDF solutions are computed by processing the range and Doppler measurements from Space Network (SN) and Doppler measurements from Deep Space Network (DSN) or Universal Space Network (USN) using the filter/backward smoother capability in the Orbit Determination Tool Kit (ODTK) program. Therefore, the FDF solutions are an independent reference for the definitive requirement assessment. Sjolowski et.al have shown that the MMS satellite spin rate (nominally about 3 Rotations per Minute) induces a large Doppler noise envelope of varying magnitude depending on the spin rate.³ Therefore, FDF uses the definitive attitude profile to model the effects of the MMS spacecraft spin in the tracking measurements,

which results in significantly smaller Doppler residuals. These solutions, referred to as “despun” solutions, are used to generate the definitive difference plots for this paper. A summary of the comparison between GEONS and FDF solutions is presented in the GEONS Definitive Performance section.

In addition, the definitive performance is routinely monitored by comparing the Navigator Single Point Solution (SPS) against the GEONS filtered solution. The Navigator SPS is computed onboard MMS whenever PR and Doppler measurements from four or more GPS Space Vehicles (SV) are available. This comparison is included in the Navigator Performance section.

MMS predictive navigation performance is evaluated by comparing the ground predictive solutions with subsequent GEONS onboard definitive solutions. The ground predictive solutions are generated in the Planning Products Functional Area (PPFA) of FDOA using FreeFlyer 6.9.1 to propagate the best available GEONS solutions (post-perigee solutions). These predictive solutions are used for maneuver planning, conjunction assessment, and scheduling and acquisition for contacts with SN, DSN, and USN. A summary of the comparison between GEONS and PPFA solutions is presented in the GEONS Predictive Performance section.

MMS maneuver planning performance is evaluated by examining the velocity errors computed from the difference in the GEONS definitive solutions and PPFA predicted solutions. The maneuver planning requirement, when applied to one-orbit and two-orbit predictions, calls for the maximum error to be reported. After reviewing the apogee-raising simulation results, the flight dynamics team decided to use predictions based on the most recent post-perigee navigation for maneuver planning during the apogee-raising campaign. This was particularly critical for the cases where maneuvers are performed for a single MMS spacecraft on consecutive orbits. A summary of the results is presented in the GEONS Maneuver Planning Performance section.

The GEONS Ground Support System (GGSS), which is a component of the FDOA ground support system, performs GEONS telemetry analysis and comparison. A significant portion of GGSS code is based on a custom MATLAB toolbox developed for the MMS mission. For many of the performance measures GGSS performs period-folded trending in mean anomaly in addition to time series. This plotting model was selected because the MMS orbits are highly elliptical. Under the assumption that performance measures are approximately stationary within small mean anomaly bins across multiple orbits, the statistics such as mean and 99% confidence interval can be computed for each bin.

GEONS PERFORMANCE ASSESSMENT RESULTS

The MMS navigation requirements were derived from the MMS mission-level science and operational support requirements. This section evaluates GEONS inflight performance in Phase 2 with respect to the associated onboard definitive navigation requirements and related ground predictive ephemeris and maneuver planning requirements. Phase 2 of MMS mission started with the apogee-raising campaign that took place from day 40 to 99 of 2017 during which a total of 32 apogee-raising maneuvers (eight on each spacecraft) were performed. Phase 2a was followed by 4 perigee-raising maneuvers (1 on each spacecraft), and then formation initialization to 160-km formation scale-size to start Phase 2b. The formation was subsequently resized to 60, 30, and 20 km scale-sizes and maintained at the 20-km formation scale-size for the remainder of Phase 2b, which continues to day 273, 2017.

GEONS definitive performance is evaluated by comparing GEONS solutions versus FDF ODTK despun solutions. Predictive performance is verified by comparing GEONS solutions vs. PPFA predictions. FDF delivered ODTK solutions for comparison with GEONS solutions three

separate times during the three-month apogee-raising campaign to provide for an adequate assessment of the definitive navigation solutions while the apogee radius gradually increased from 12 Re to 25 Re. In this paper, the definitive performance in Phase 2a is presented by showcasing the results over a 5-day period spanning from day 61 to 66 of 2017. For Phase 2b, the results are presented over a 9-day period, spanning from day 169 to 178 of 2017. In Phase 2a, the maneuver performance is discussed in detail by examining the most difficult case in meeting the requirement, where two consecutive maneuvers are applied to a single MMS spacecraft. In Phase 2b, the maneuver performance for the pair of formation resize maneuvers to 30-km scale-size are discussed in detail. The results presented in this section demonstrate that all definitive, predictive, and maneuver planning requirements are met in Phase 2a and 2b.

GEONS Definitive Performance

The following definitive absolute accuracy requirements apply to the navigation solutions in both Phase 2a and 2b.

- The absolute orbital positions shall be known within 100 km.
- During the science RoI, the Semi-Major Axis (SMA) accuracy shall be better than 100 m.

The following definitive relative accuracy requirements apply to the navigation solutions in Phase 2b except during maneuver recovery periods. During Phase 2b, the science RoI is the orbital region above 15 Re.

- During the science RoI, the separation distance between any pair of MMS spacecraft shall be known to within the greater of 1% or 100 m, whichever is greater.
- During the science RoI, the relative SMA (RSMA) accuracy shall be better than 140 m.

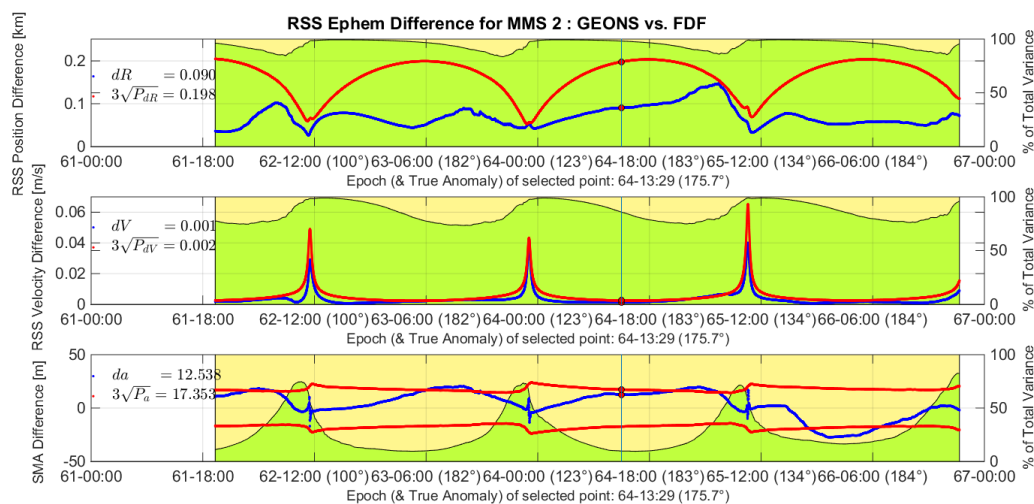


Figure 1. GEONS vs FDF Definitive Comparison, Phase 2a

Figure 1 shows a typical comparison of the GEONS and FDF solutions. In the top two subplots, the root-sum-squared (RSS) position differences and RSS velocity differences are plotted in blue. In the third subplot, the SMA differences are plotted in blue. The value of three times the formal error of the RSS differences, computed by adding the variance from individual estimator covariance matrices, is plotted in red. The values given in the upper left corner of each subplot correspond to

the points selected by the vertical line and for the epoch and true anomaly is shown on the x-label. The percentage of the individual contributions of the FDF and GEONS formal variances to the variance of the differences is shown in the green and tan overlays, respectively.

The comparison shown in Figure 1 is for a period in the middle of apogee-raising campaign (from day 61 to 66 of 2017), when the apogee radius is about 16 Re. Figure 1 shows that the GEONS vs. FDF RSS position differences on MMS 2 are less than 150 m. Reviewing the plots generated for all four MMS spacecraft shows that the GEONS vs. FDF RSS position differences do not exceed 200 m. When the apogee radius increased to 25 Re at the end of the apogee-raising campaign, the maximum RSS position differences increased to 300 m. Note that the formal errors are much larger for the FDF solution (green overlay) than for the GEONS solution (tan overlay) because the ground tracking schedule consisted of short pre-perigee and post-perigee SN contacts and one DSN Doppler-only contact per day near apogee; whereas, the GEONS solutions are based on near-continuous GPS PR measurements.

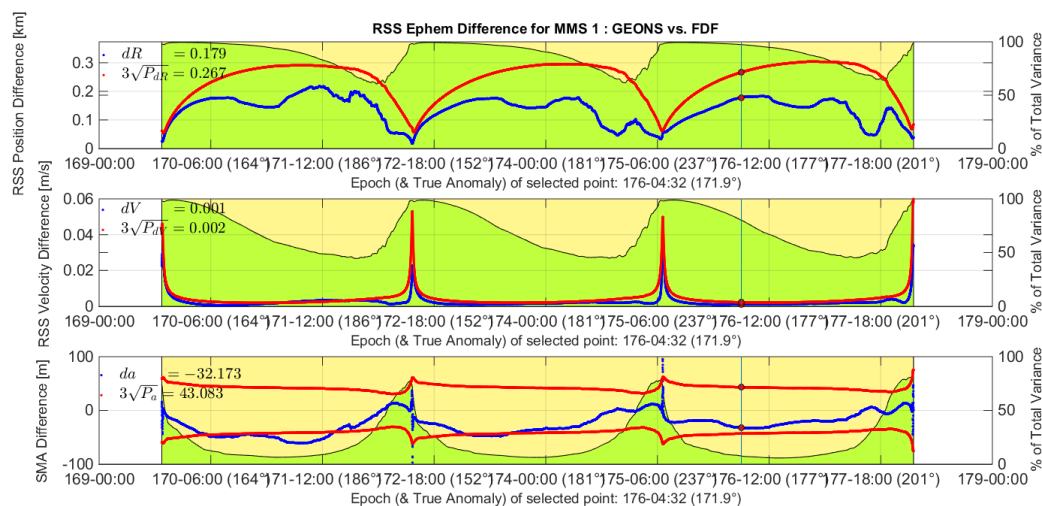


Figure 2. GEONS vs. FDF Definitive Comparison, Phase 2b

Figure 2 compares the GEONS and FDF navigation solutions for MMS 1 during Phase 2b, from day 169 to 178 in 2017. During this 9-day period, no resize or maintenance maneuvers were performed on any of the MMS spacecraft, resulting in the best comparison between GEONS and FDF solutions. The maximum RSS position differences are less than 250 m, a typical value for all four MMS. This result is consistent with the comparisons made at the end of apogee-raising campaign.

The RSS position difference values, found in Figure 1 and Figure 2 and the corresponding plots generated for all other MMS spacecraft, confirm that the definitive requirement on absolute orbital position is met with a large margin in Phase 2. Due to the increased apogee radius, MMS spacecraft track a fewer number of GPS SV at apogee in Phase 2, therefore GEONS solutions are expected to be less accurate when compared to Phase 1 solutions (see the Navigator Performance section). Further, FDF solutions are less accurate around apogee since only the Doppler measurements from DSN are available to FDF. The GEONS vs. FDF definitive differences increased in Phase 2 as compared to Phase 1, where RSS position differences were typically below 150 m, and during GEONS commissioning, where differences were as good as 50 m¹.

The maximum SMA differences in the RoI, computed based on the GEONS and FDF solutions, are typically 20-30 m in Phase 2a and 50-70 m in Phase 2b, as shown in the third subplot of Figure

1 and Figure 2, respectively. For reference, the SMA differences in Phase 1 were typically less than 5-10 m¹. In Phase 2a (Figure 1), the maximum SMA differences occur at the apogees with smaller spikes at the perigees. In Phase 2b (Figure 2), the maximum SMA differences occur at the perigees (outside the RoI). The SMA difference values found in Figure 1 and Figure 2 and the similar plots generated for all other MMS spacecraft demonstrate that the definitive requirement on SMA accuracy of 100 m is met in Phase 2 during the science RoI.

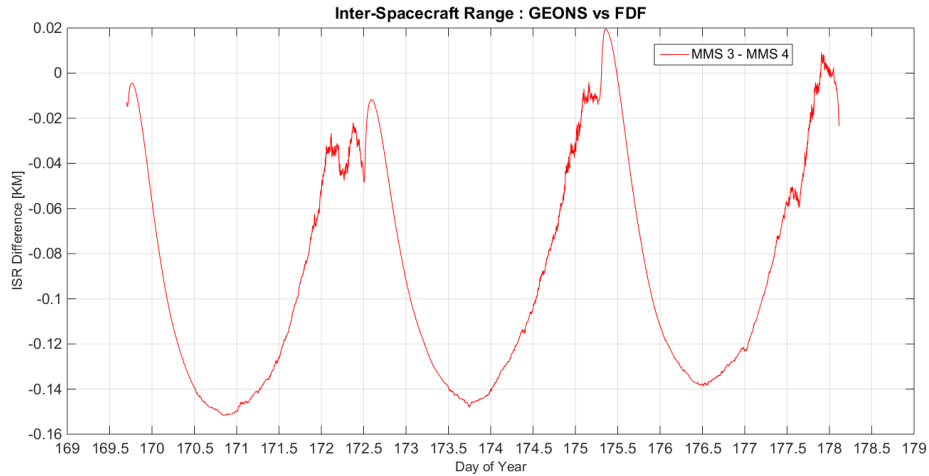


Figure 3. GEONS vs. FDF Inter-Spacecraft Range Comparison, Phase 2b

Figure 3 shows the difference in Inter-Spacecraft Range (ISR) of MMS 3 and MMS 4, computed based on GEONS and FDF solutions, from day 169 to 178 of 2017 in Phase 2b. Among all pairs of MMS, the plot for MMS 3 - MMS 4 pair shows the largest difference during this period. To meet the relative definitive requirement, the separation distance must be known to within the greater of 1% of the ISR or 100 m, whichever is greater. During the 9-day period shown in Figure 3, the MMS formation was at 30-km scale-size over the science RoI. As seen in Figure 3, the plot of ISR difference is below 160 m throughout the comparison period, confirming that the separation accuracy is better than the required value of 300 m.

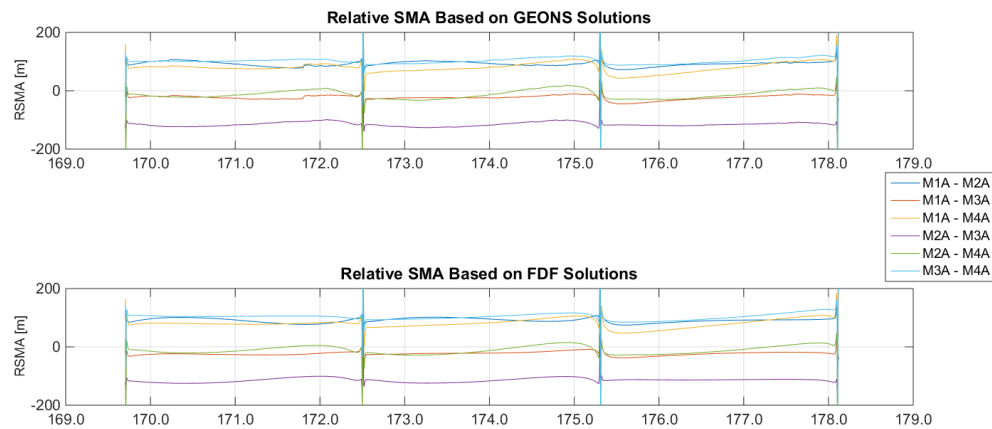


Figure 4. Relative SMA Comparison, Phase 2b

Figure 4 shows the relative SMA among all pairs of MMS spacecraft during the 9-day period in Phase 2b when the definitive requirement comparison was conducted. The top subplot shows the RSMA values based on GEONS solutions and the bottom subplot shows the RSMA results based on FDF solutions. The spikes in the RSMA occur near each perigee. Comparing the two subplots indicates that the RSMA values computed based on these two solutions are very close and the differences are within a small fraction of the 140 m requirement over the science RoI (above 15 RE).

In summary, the FDF's navigation solutions provided an independent source to evaluate the MMS onboard navigation definitive performance. These comparisons confirm that the GEONS onboard solution meets the definitive requirements in Phase 2a and 2b with significant margins.

GEONS Predictive Performance

The following MMS predictive requirements were derived to support the accuracy needed for establishing communication with the DSN, USN and SN stations:

- To meet the DSN and USN acquisition requirement, the magnitude of the RSS position errors shall not exceed 27 km after 1-day prediction.
- To meet the SN acquisition requirement, the magnitude of the RSS position errors shall remain below 19.6 km and 23.5 km after 1-day prediction in Phase 2a and Phase 2b, respectively.

GEONS predictive performance is evaluated by comparing GEONS and PPFA solutions. The PPFA orbit solutions are generated by initializing the ephemeris predictions from GEONS solutions, typically downloaded at the end of SN post-perigee contacts. These GEONS solutions are the most accurate navigation solutions available for each orbit since the MMS GPS receiver typically tracks a maximum of 12 GPS SVs below the GPS constellation.

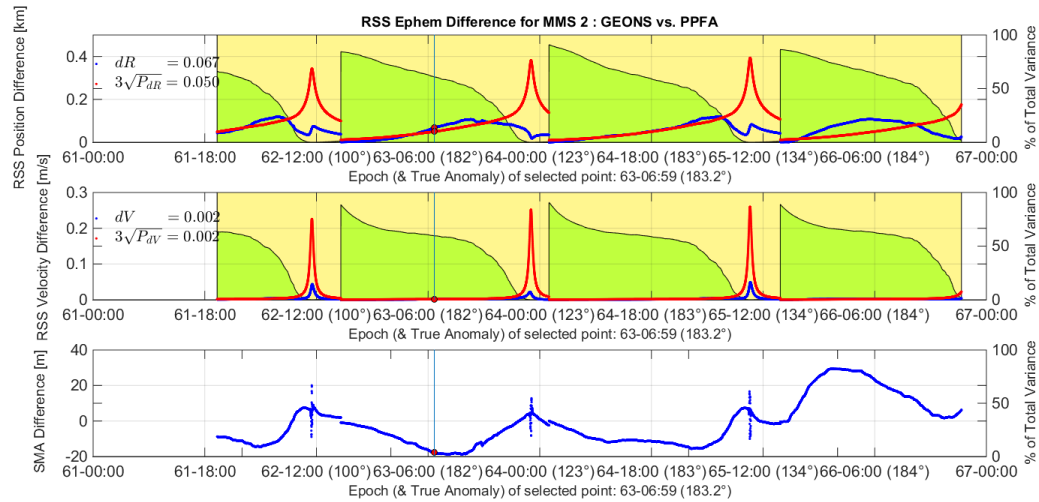


Figure 5. GEONS vs PPFA Predictive Comparison, Phase 2a

Figure 5 compares the GEONS definitive with the PPFA prediction for MMS 2 from day 61 to 66 in Phase 2a. During this 5-day period, MMS 2 did not have any apogee-raising maneuver. For the GEONS vs. PPFA comparisons generated for all MMS spacecraft from beginning through middle of the apogee-raising campaign, the RSS position differences typically remain below 150 m except near the perigees, where the differences typically increase. By the end of the apogee-raising

campaign (not shown in this paper), the RSS position differences computed for GEONS vs. PPFA solutions slowly increased but remained below 750 m except at the perigees, where the differences were as large as 3.5 km. The larger differences in position and velocity near perigee are primarily due to propagation errors introduced using a 30-second fixed integration step for propagation in PPFA; whereas, a 10-second step is optimal for accurate propagation near perigee of the highly elliptical orbits. This is a compromise introduced to reduce computational throughput.

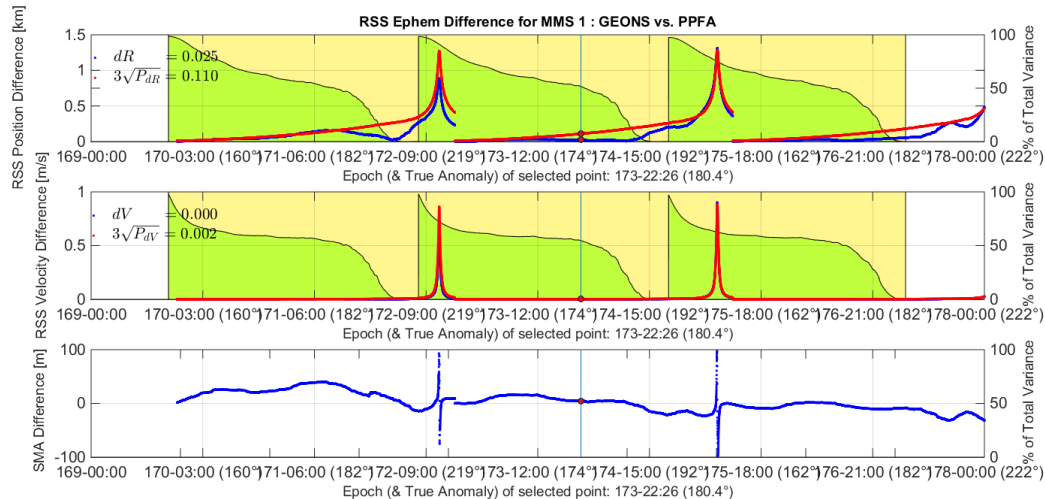


Figure 6. GEONS vs. PPFA Predictive Comparison, Phase 2b

Figure 6 compares the GEONS definitive with the PPFA prediction for MMS 1 from day 169 to 178 in Phase 2b. This comparison shows a close agreement between the GEONS and PPFA solutions since resize or maintenance maneuvers were not performed on any MMS spacecraft during this 9-day period. The GEONS vs. PPFA comparison plots generated for all MMS spacecraft show that the RSS position differences typically remain below 300 m except at the perigees, where the differences typically increase (1.3 km on MMS 1 as shown in Figure 6, but typically can reach to 3 km when the plots for other MMS are examined).

The RSS position differences shown for MMS 1 in Figure 5 and Figure 6 and the results obtained for all other MMS spacecraft confirm that the predictive requirements for ground and space network acquisition accuracy are met with large margins in Phase 2. As expected, the GEONS definitive vs. PPFA prediction differences increased in Phase 2 as compared to Phase 1, where the RSS position differences were typically below 200 m, and during GEONS commissioning, where differences were as good as 80 m¹.

GEONS Maneuver Planning Performance

Phase 1 of the MMS mission started in July 2015 and ended in February 2017, while during the last six months of the mission (small formation period) the formation scale-size was maintained at 7 km⁴. The transition to Phase 2 was achieved by first resizing the Phase 1 formation to 60-km scale-size through a pair of Formation Maneuvers (FM1 and FM2) on each MMS on days 32 and 33, 2017. Then each spacecraft performed eight apogee-raising maneuvers over a period of two months from day 40 to 99, 2017, while each MMS spacecraft apogee was gradually increased from 12 Re to 25 Re.

Phase 2a maneuvers were executed in four stages (aka snakes), with each MMS executing a pair of apogee-raising maneuvers in each snake. The apogee-raising maneuvers were performed in the following order: [1 2 3 4 4 3 2 1], [4 1 2 3 3 2 1 4], [3 4 1 2 2 1 4 3], [2 3 4 1 1 4 3 2]. The maneuvers

were performed on consecutive perigees, except when a spacecraft had two maneuvers back-to-back (e.g. MMS 4 in snake 1 and MMS 3 in snake 2); in this case a perigee was skipped between the two maneuvers. Since the Navigator tracks and processes up to 12 simultaneous GPS PR measurements during the perigee, this strategy allowed the GEONS navigation solutions on the maneuvering MMS spacecraft to fully converge following the first maneuver and before the next maneuver. In addition, a perigee was skipped between snakes 1, 2 and snakes 2, 3 to allow an extra time to handle potential maneuver contingencies and staffing maneuver shifts.⁵

The following maneuver planning requirement applies to each component of the predicted velocity vector just prior to each AR maneuver:

- In Phase 2a, the predicted velocity errors should not exceed the 1% of the associated delta-V component or 10 mm/s, whichever is greater.

The maneuver planning predictions are made from the navigation solutions downloaded at the SN post-perigee contacts, one orbit and two orbits prior to the maneuver. The maneuver planning accuracy is assessed by comparing the maximum predicted velocity errors just prior to the start of the maneuver against the requirement. In the following, the plots of one-orbit and two-orbit predictions are shown side-by-side for velocity errors along the x, y, and z components in J2000 coordinate system. On each subplot, an arrow displays the start of the maneuver at which the velocity error is obtained. The accuracy of the maneuver planning predictions in Phase 2a are examined below for two consecutive AR maneuvers on MMS 2 in snake 3, AR 725 and AR 727, where the three-digit numbers represent the orbit revolution numbers.

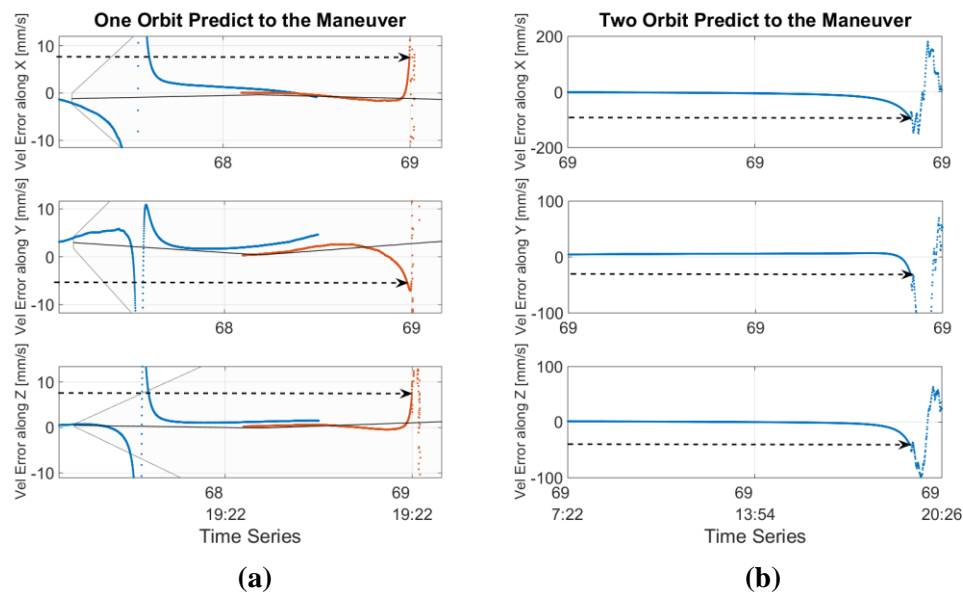


Figure 7. Predicted Velocity Differences Prior to AR 725 for MMS2

Figure 7 shows the differences in the PPFA predicted velocity and the GEONS definitive velocity components in the Mean of J2000 inertial frame prior to AR 725 maneuver. Figure 7(a) shows the velocity differences (plotted in orange) based on predictions made from the GEONS solutions downloaded at the SN contact one orbit prior to the maneuver and the velocity differences for the previous one orbit prediction (plotted in blue). Figure 7(b) shows the velocity errors (plotted in blue) based on the solutions downloaded at the SN contact two orbits prior to the maneuver. For AR maneuvers, the delta-V components in the Mean of J2000 frame are typically about 35 m/s for x, 10 m/s for y, and 2 m/s for z⁵. Therefore, the corresponding requirement values (the greater of

1% of the maneuver components or 10 mm/s) are about 350 mm/s, 100 mm/s, and 20 mm/s in the Mean of J2000 x, y, and z directions. In Figure 7, the arrows point to the difference values at the times where the requirement applies.

Comparing the results of one-orbit and two-orbit predictions in Figure 7 indicates that the largest velocity differences occur for the two-orbit predictions. This is a typical result for the AR maneuvers during Phase 2a. Based on the one-orbit prediction to AR 725 (Figure 7 (a)) the absolute value for the velocity errors along x, y, z are about 8 mm/s, 5 mm/s, and 8 mm/s, respectively. From two-orbit prediction to AR 725 (see Figure 7 (b)), the absolute values for the velocity errors along x, y, z are 100 mm/s, 40 mm/s, and 40 mm/s, respectively. Therefore, the one-orbit predictions meet the requirement for all the components, and the two-orbit predictions meet the requirement for the x and y components but not the much smaller z component. The accuracy of the maneuvers planned/executed during Phase 2a exceeded the flight dynamics team expectations⁵, which indicates that the maneuver planning requirement 10 mm/s threshold for the two-orbit predictions is probably tighter than needed.

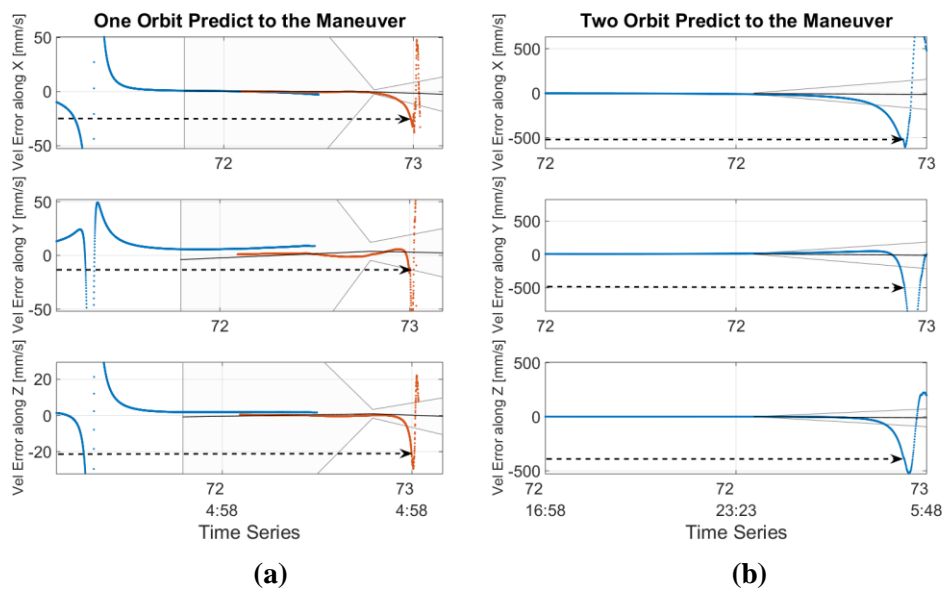


Figure 8. Predicted Velocity Differences Prior to AR 727 for MMS2

Figure 8 shows similar plots of velocity differences for one-orbit and two-orbit predictions prior to AR 727 maneuver. The maximum velocity differences occur for the two-orbit prediction. Figure 8(a) shows that the absolute values of the velocity differences just prior to AR727 along x, y, z are about 25 mm/s, 13 mm/s, and 21 mm/s, respectively. From Figure 8(b) the absolute values for the velocity differences along x, y, z are about 500 mm/s, 500 mm/s, and 390 mm/s, respectively. For AR 727, the results from the two-orbit predictions exceed the requirement along all components, whereas the results from the one-orbit predictions meet the requirement along x and y components but not the much smaller z component. The two-orbit prediction for AR 727 starts from the navigation solutions downloaded at the SN post-perigee contacts immediately following AR 725, thus larger navigation errors are expected. Based on the simulation analysis performed prior to the apogee-raising campaign, the FDOA team had decided to use the most recent post-perigee navigation solutions (one-orbit predictions) for planning of the consecutive maneuvers on a single MMS spacecraft.

There are two main differences between the apogee-raising maneuvers and the resize and maintenance maneuvers (performed during Phase 1 and Phase 2b). First, apogee-raising maneuvers are centered around perigee, whereas formation resize and formation maintenance maneuvers are performed around apogee and on the orbit flanks. The velocity errors are the largest near perigees (e.g., see Figure 5). Therefore, the predicted velocity errors are typically smaller at the times of the resize and maintenance maneuvers than for the apogee-raising maneuvers. Another difference is that the apogee-raising maneuvers are at least an order of magnitude larger than resize and maintenance maneuvers (exp. AR 35 m/s vs. resize 0.3-3.0 m/s). A larger maneuver does not have any direct effect on the navigation performance unless the solutions immediately following the maneuver are used in prediction and planning.

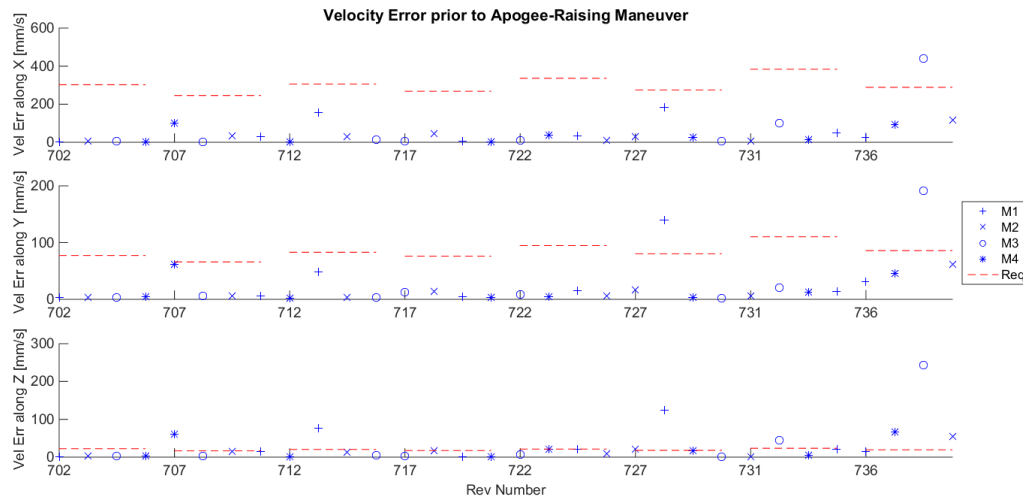


Figure 9. Velocity Differences Prior to Each Apogee-Raising Maneuver vs. Requirement

Figure 9 shows the predicted vs definitive velocity differences in the x, y, and z components based on one-orbit predictions and the respective requirement for all AR maneuvers on all four MMS collectively. As discussed earlier, the velocity errors along z component often do not meet the requirement since AR maneuvers typically have the smallest delta-V z components and the navigation errors at the perigees prior to AR maneuvers are typically larger than 20 mm/s. In Figure 9, the four stages (snakes) of the apogee-raising campaign are displayed in two sets (legs), each comprised of four maneuvers. The first leg of snake 4 consists of the largest maneuvers (about 40 m/s), which possibly contributed to larger differences seen in the second leg of snake 4, therefore meeting the requirements fewer times.

Following Phase 2a maneuvers, four perigee-raising maneuvers (one per MMS spacecraft) were performed on day 106, 2017. Phase 2b formation initialization maneuvers were performed on day 116 and 122, 2017 to bring the four MMS into a 160-km scale-size. During the first couple of months of Phase 2b, the formation was downsized to 60, 30, and 20 km scale-sizes about every 2-4 weeks. This section discusses the results of the resize maneuvers to 30 km formation to evaluate the maneuver planning requirements in Phase 2b.

The resize and maintenance maneuvers consist of two maneuvers in consecutive orbits, FM 1 and FM 2. The following requirements apply to each maneuver pairs in Phase 2b.

- The maximum velocity errors along each component prior the first maneuver (FM 1) shall not exceed the 1% of the associated delta-V component or 10 mm/s, whichever is greater. The

maximum error is obtained by comparing the predictions made from SN post-perigee solutions, one and two orbits prior to the maneuver.

- The velocity error components prior to the second maneuver (FM 2) shall not exceed the 1% of the associated delta-V component or 2 mm/s, whichever is greater. The velocity error prediction is made from the SN post-perigee solutions obtained between FM 1 and FM 2.

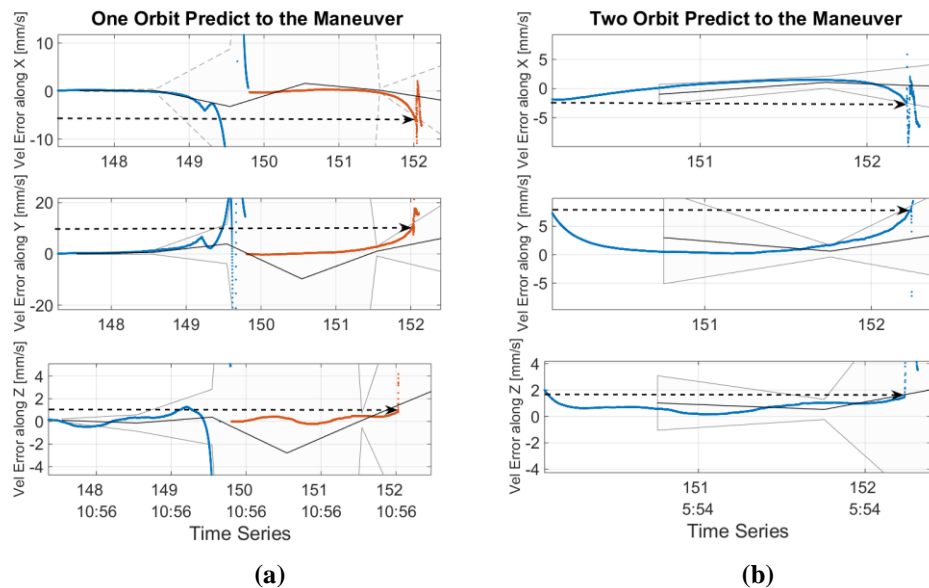


Figure 10. Predicted Velocity Differences Prior to FM 1 of 30-km Resize Maneuver for MMS1

Figure 10(a) shows the velocity differences for one-orbit prediction (in orange) and Figure 10(b) shows the velocity errors for two-orbit predictions (in blue) prior to the first maneuver (FM 1) in the Phase 2b 30-km resize maneuvers. The arrows point to the velocity errors at the start of the maneuvers. The maneuver components are less than 500 mm/s; therefore, 10 mm/s becomes greater than the 1% of the delta-V components and thus sets the requirement value. Figure 10(a) shows that the absolute value for the velocity errors along x, y, z are about 6 mm/s, 10 mm/s, and 1 mm/s, respectively. From Figure 10(b) the absolute values for the velocity errors along x, y, z are about 2.5 mm/s, 7.5 mm/s, and 1.8 mm/s, respectively. Figure 10 shows that the requirement is met along all velocity components for FM 1. This is the typical result for all FM 1 maneuvers for the resizes performed to date in Phase 2b, where the maneuver planning requirement is met or if missed the margin is very narrow.

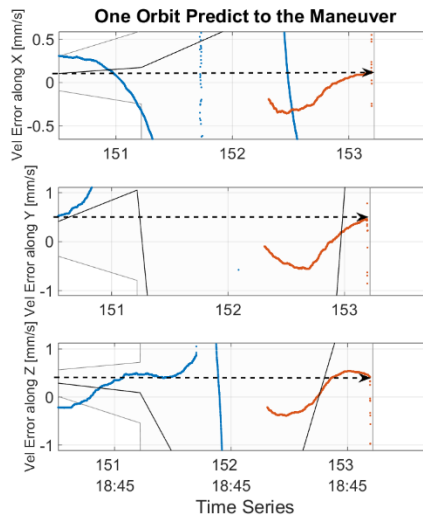


Figure 11. Predicted Velocity Differences Prior to FM 2 of 30-km Resize Maneuver for MMS 1

Figure 11 shows the velocity differences for one-orbit prediction (in orange) prior to FM 2 maneuver in the resize to 30-km formation. The velocity differences are below 2 mm/s and within the tightest requirement on each maneuver component. The requirement on FM 1 is usually met with a larger margin than the requirement on FM 2. Since these maneuvers are applied in consecutive orbits, the navigation solutions that are used to plan FM 2 usually result in a less accurate predictions because they either contain the definitive or predictive errors from the execution of FM 1. The post FM 1 navigation solutions that include the definitive navigation errors are sometimes preferred to plan FM 2 but preparing and uploading maneuver commands for the fleet of MMS spacecraft following FM 1 and prior to the start of FM2 is operationally challenging and risky. FDOA has to-date used the navigation solutions prior to FM 1 to plan both FM 1 and FM 2 maneuvers, therefore only the predictive navigation errors are included in the planning of FM 2. Nonetheless, the FM 2 plans are always verified against the plans based on the post FM 1 navigation solutions prior to the execution of FM 2.

Navigator Performance

The MMS Navigator receiver has proven to be a reliable source of GPS measurements for GEONS even when the MMS spacecraft is well above the GPS constellation. This section discusses the Navigator product data associated with GEONS performance. These are 1) the number of GPS SVs tracked by MMS spacecraft and 2) the SPS solutions that are used for comparison with GEONS solutions. The Navigator receiver acquires and tracks GPS transmitter side-lobe signals with carrier-to-noise spectral density (C/N_0) levels below 25 db-Hz². Below, the plots displaying the results for these performance measures are provided for both Phase 2a and Phase 2b.

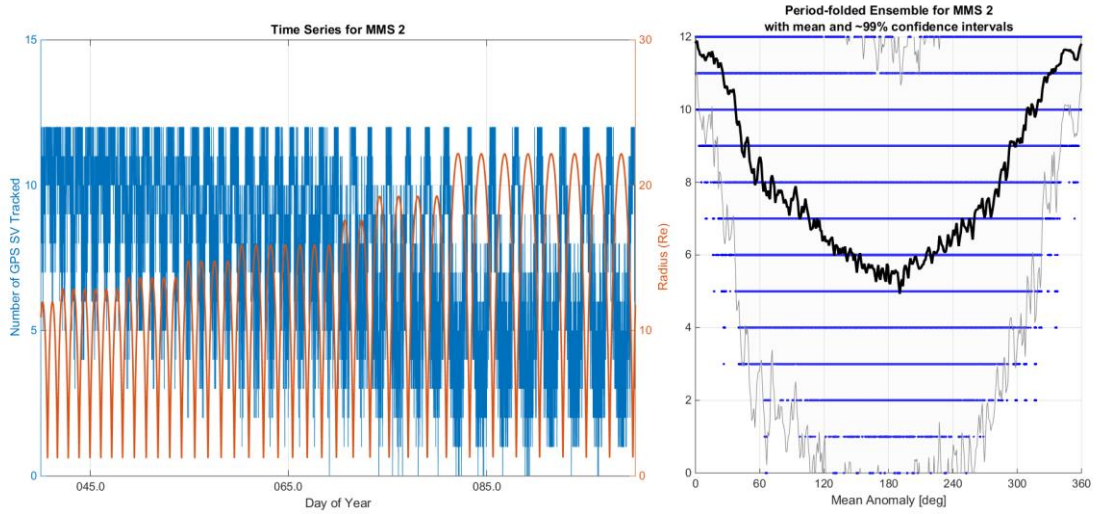


Figure 12. Number of GPS SVs, Phase 2a

Figure 12 displays the number of GPS SVs as a function of time (left) and mean anomaly (right) for MMS 2 during the entire period of apogee-raising campaign from day 40 to 99. The subplot on the left shows the number of GPS SVs in blue and the radius in orange. As the apogee radius increased from 12 Re to 25 Re, the number of tracked GPS SVs were decreased near apogee. The average number computed over the consecutive orbits remained greater than five as shown with the heavy black line in the subplot on the right, where the grey line gives the 99% confidence envelop during the entire apogee-raising period.

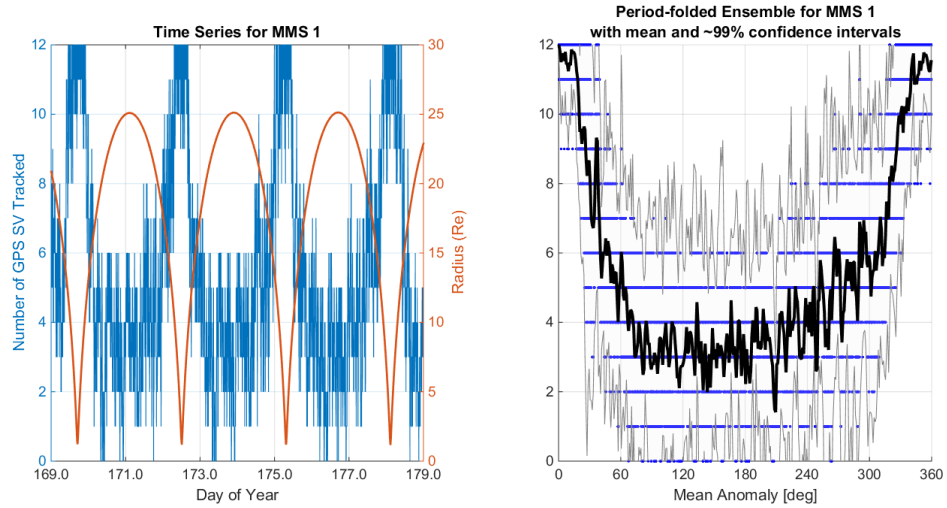


Figure 13. Number of GPS SVs, Phase 2b

Figure 13 shows the number of GPS SVs tracked by MMS 1 as a function of time and mean anomaly from day 169 to 178 (associated with the Phase 2b period during which the comparisons for definitive and predictive performance assessment were made in this paper). The subplot on the left shows that around apogee (25 Re), there are periods when the number of GPS SVs tracked (plotted in blue) drops to zero. The average number computed over the consecutive orbits remains greater than one as shown with the heavy black line in the subplot to the right. Comparing Figure

12 and Figure 13 shows that the number of GPS SVs tracked by MMS spacecraft has significantly dropped in Phase 2b except near perigee, where the average number remains 12. The performance of GEONS during Phase 2b remains excellent because the GEONS accuracy is strongly influenced by the maximum available PR measurements as MMS spacecraft fly through each perigee.

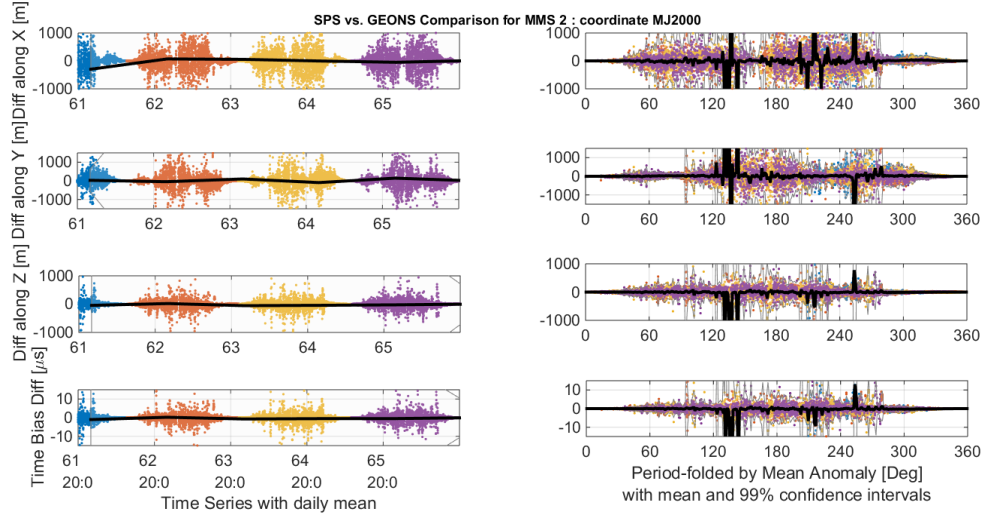


Figure 14. SPS vs. GEONS Definitive Comparison, Phase 2a

Figure 14 compares the position and time bias estimates between the Navigator's SPS and GEONS solutions. The subplot on the left gives the differences as a function of time and the subplot on the right gives the period-folded differences over five orbits as a function of Mean Anomaly. The position component differences in the Velocity (V) / Normal (N) / Binormal (B) frame are within ± 1000 m over most of the orbit and within ± 50 m near perigee. The heavy black line on the left subplot shows the average differences computed over a 24-hr window. The heavy black line on the right subplot shows that the average differences computed over a 1-degree bin in Mean Anomaly are typically much smaller at perigee than near apogee. Also, the spikes in the right subplot are larger when compared to Phase 1 results¹. This is explained by noticing that due to an increase in the apogee radius, fewer GPS PRs are measured near apogee, resulting in the SPS solutions with poorer geometry, i.e. larger Geometric Dilution of Precision (GDOP). Further, comparing the results in Figure 1 (GEONS vs. FDF) and Figure 14 (SPS vs. GEONS) indicates that the accuracy of GEONS position solutions is significantly higher than the Navigator's SPS position solutions for all time periods except near perigee.

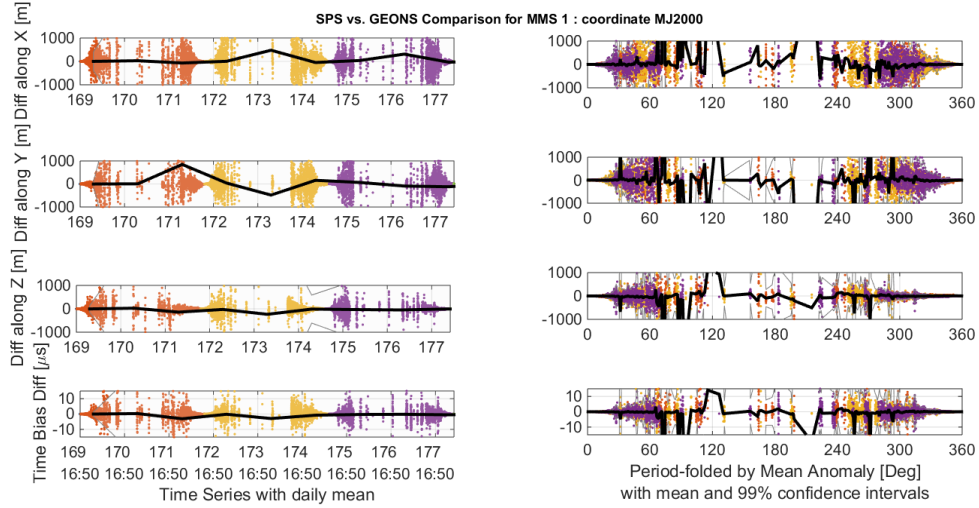


Figure 15. SPS vs. GEONS Definitive Comparison, Phase 2b

Figure 15 shows a similar comparison of SPS vs. GEONS solutions from day 169 to 178 during Phase 2b (the same 9-day period for which other Phase 2b comparisons were presented in this paper). Comparing Figure 15 and Figure 14 shows that fewer SPS solutions are available over the apogee region in Phase 2b since fewer number of GPS SVs are tracked at higher altitudes. Also, the spikes associated with large differences in SPS and GEONS solutions are more dominant. Although, fewer GPS SVs are tracked and fewer SPS solutions are available around apogee in Phase 2b, the agreement of the Navigator SPS and GEONS solutions around perigee remains the same as in Phase 1¹.

CONCLUSION

The Navigator/GEONS performance during the apogee-raising campaign and Phase 2b has exceeded the expectations based on prelaunch simulations. Comparing Phase 2 results with Phase 1 results shows that the errors have increased in Phase 2b mainly because, 1) fewer GPS SVs are tracked due to flying at higher altitudes above GPS constellation, 2) the predictions from post-perigee navigation solutions are longer due to the larger orbital period. Phase 2b of the MMS mission will continue until day 273, 2017. The current plan is to extend the MMS mission beyond its official ending for at least two years. During the extended mission, there will be another apogee-raising campaign, increasing the apogee radius to 28 Re. Considering the results presented in this paper, MMS navigation team is confident that GEONS solutions will remain reliable and GEONS performance will stay consistent with Phase 2b.

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